Transitions in Programming Models

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Significant Transitions

- Programming languages (PLs)
  - They evolve slowly and occasionally, e.g.:
    - C to C++ : More robust data structures (objects)
    - C++ to Java : More robust control flows (strong typing)
  - But new *programming models* are invented routinely
    - As domain-specific libraries or API's
    - As program analysis tools
    - As language extensions
- Transitions
  - Significant transitions in programming models eventually "precipitate" into new programming languages (unpredictably)
  - We can watch out for significant transitions in programming models

Transitions in 3 (related) areas

- We are in the middle of a radical transition in programming models (and eventually PLs)
- A new emphasis on computation on WANs
  - Wide area flows
    - Messages nor RPC, schedules not threads. *Messaging API's.*
    - Need to integrate these new flows into PL control constructs.
  - Wide area data
    - XML is "net data". *XML API's.*
    - Need to integrate this new data into PL data structures.
  - Wide area protection
    - Access control, data protection. *Security and privacy API's.*
    - Need to integrate security properties into PL assertions.
- Disruptive transitions
  - Forget RPC (and threads): the world is asynchronous.
  - Forget type systems as we know them.
  - Forget trusting anything non-local.

Flow Integration

- Wouldn't it be nice to hide concurrency from programmers?
  - SQL does it well
  - UI packages do it fine (mostly single-threaded!)
  - RPC does it ok
  - But we are moving towards more asynchrony, I.e. towards more visible concurrency (e-commerce scripts and languages, web services, etc.)

    You can hide all concurrency some of the time, and you can hide some concurrency all the time, but you can't hide all concurrency all the time.
  - Asynchronous message-based concurrency does not fit easily with more traditional shared-memory synchronous concurrency control
- Goal: make concurrent flows available and checkable at the language level.

Data Integration

- Wouldn't it be nice to "program directly against the schema" in a well-typed way?
  - PL data has traditionally been "triangular" (trees), while persistent data has traditionally been "square" (tables)
  - This has caused integration problems: the “impedance mismatch” in data base programming languages
  - Now, persistent data (XML) is triangular too!
  - However, the type systems for PL data (based on tree matching) and XML (based on tree automata) are still deeply incompatible
- Goal: make semistructured data easily available and checkable at the language level.

Protection Integration

- Wouldn't it be nice to have automatic security?
  - It's an applet. Sits is a sandbox. End of story. (?)
  - Ok, what about *semi-automatic* security? Explicitly grant/require permissions. (Stack walking etc.)
  - Leads to "sophisticated" access models that programmers do not understand reliably.

- Security today: obscure mechanisms to prevent *something* from happening.
  - It is usually not clear what security mechanisms are meant to *achieve*.
  - Need to move towards *declarative* security and privacy interfaces and policies.
- Goal: make protection policies available and checkable at the language level.

Language Reliability

- Whether or not we merge new programming models into PLs, we need analysis tools for these new situations
  - Flow: e.g.: behavioral type/analysis system
    - "Does the program respect the protocol?"
  - Data: e.g.: semistructured type/analysis systems
    - "Does the program output match the schema?"
  - Protection: e.g.: information-flow type/analysis system
    - "Does the program defy policy or leak secrets"
- Analysis tools are critical for software reliability
  - Getting it right without assistance is just too hard.
  - These technologies need to be developed in any case.

A Personal Agenda

- Flows [exploit join calculus]
  - Synchronization chords
  - Cω (f.k.a. Polyphonic C#)
- Data [exploit spatial logics as types]
  - Description logics
  - Cω (f.k.a. Xen/X#)
- Protection [exploit π-calculus-style restriction]
  - Flows: Secrecy and Group Creation
  - Data: Trees with hidden labels

Flows

Language Support for (WAN) Distribution

- Distribution $\Rightarrow$ concurrency + latency
  $\Rightarrow$ asynchrony
  $\Rightarrow$ more concurrency
  - Approaches: Message-passing, event-based programming, dataflow models, etc.
  - Languages: coordination (orchestration) languages, workflow languages, etc.

- Good language support for asynchrony
  - Make invariants and intentions more apparent (part of the interface), because:
    - It's good software engineering
    - Allows the compiler much more freedom to choose different implementations
    - Also helps other tools

~~Polyphonic C#~~ Cω

- An extension of the C# language with new concurrency constructs
- Based on the join calculus
  - A foundational process calculus like the π-calculus but better suited to asynchronous, distributed systems.
  - First applied to functional languages (JoCaml).
  - It adapts remarkably well to o-o classes and methods.
- A single model that works for
  - Local concurrency (multiple threads on a single machine).
  - Distributed concurrency (asynchronous messaging over LAN or WAN).
  - With no distributed consensus.
- It an unusual model. But it's also a simple extension of familiar o-o notions.
  - No threads, no locks, no fork, only *join*.

In one slide:

- Client Side (method invocation)
  - Objects have both synchronous and *asynchronous* methods.
  - If the method is synchronous, the caller blocks until the method returns some result (as usual).
  - If the method is async, the call completes at once and returns void (as in message passing).
- Server Side (class definition)
  - A class defines a collection of *chords* (method synchronization patterns), which define what happens once a particular *set* of methods have been invoked. One method may appear in several chords.
  - When enough pending method calls match a chord pattern, the chord body runs. If there are several matches, an unspecified chord is selected.
  - Each chord can have *at most* one synchronous method (providing the *result*). A chord containing *only* asynchronous methods effectively forks a new thread.

A simple unbounded buffer

```
class Buffer {
  String get() & async put(String s) {
      return s;
  }
}
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- An asynchronous method header (hence returning no result), with a string argument

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- An ordinary (synchronous) method header with no arguments, returning a string
- An asynchronous method header (hence returning no result), with a string argument
- Joined together in a chord with a single body

A simple unbounded buffer

```
class Buffer {
  String get() & async put(String s) {
    return s;
  }
}
```

- Calls to `put()` return immediately (but are internally queued if there's no waiting `get()`).
- Calls to `get()` block until/unless there's a matching `put()`
- When there's a match the body runs, returning the argument of the `put()` to the caller of `get()`.
- Exactly which pairs of calls are matched up is unspecified.

A simple unbounded buffer

```
class Buffer {
  String get() & async put(String s) {
    return s;
  }
}
```

- Does *this* example involve spawning any threads?
  - No. Though the calls will usually come from different pre-existing threads.
- So is it thread-safe? You don't seem to have locked anything…
  - Yes. The chord compiles into code which uses locks. (And that *doesn't* mean everything is synchronized on the object.)
- Which method gets the returned result?
  - The synchronous one. And there can be at most one of those in a chord.

Reader/Writer

…using threads and mutexes in Modula 3

An introduction to programming with threads. Andrew D. Birrell, January 1989.

```
VAR i: INTEGER;
VAR m: Thread.Mutex;
VAR c: Thread.Condition;

PROCEDURE AcquireExclusive();
BEGIN
    LOCK m DO
        WHILE i # 0 DO Thread.Wait(m,c) END;
        i := -1;
    END;
END AcquireExclusive;

PROCEDURE AcquireShared();
BEGIN
    LOCK m DO
        WHILE i < 0 DO Thread.Wait(m,c) END;
        i := i+1;
    END;
END AcquireShared;

PROCEDURE ReleaseExclusive();
BEGIN
    LOCK m DO
        i := 0; Thread.Broadcast(c);
    END;
END ReleaseExclusive;

PROCEDURE ReleaseShared();
BEGIN
    LOCK m DO
        i := i-1;
        IF i = 0 THEN Thread.Signal(c) END;
    END;
END ReleaseShared;
```

An integer i represents the lock state:

-1 ←→ 0 ←→ 1 ←→ 2 ←→ 3 …

(exclusive) (available) (shared)

Reader/Writer in five chords

```
public class ReaderWriter {
  public void AcquireExclusive() & async Idle() {}
  public void ReleaseExclusive() { Idle(); }

  public void AcquireShared() & async Idle()    { S(1); }
  public void AcquireShared() & async S(int n) { S(n+1); }
  public void ReleaseShared() & async S(int n) {
    if (n == 1) Idle(); else S(n-1);
  }

  public ReaderWriter() { Idle(); }
}
```

A single private message represents the state:

none ←→ `Idle()` ←→ `S(1)` ←→ `S(2)` ←→ `S(3)` …

(exclusive) **(available)** **(shared)**

A pretty transparent description of a simple state machine.
Moreover, the synchronization patters are apparent in the class interface,

Features

- A clean, simple, new model for asynchronous concurrency
  - Minimalist design – to build whatever complex synchronization behaviors you need
  - Easier to express and enforce concurrency invariants; not "buried in the code" any more
  - Much better than programming reactive state machines by hand (the complier does it for you).
  - Efficiently compiled to queues, automata, match bit-vectors, and thread pools.
  - Compatible with existing constructs, though they constrain our design somewhat
  - Solid foundations, on which to build analysis tools.

Ongoing Work

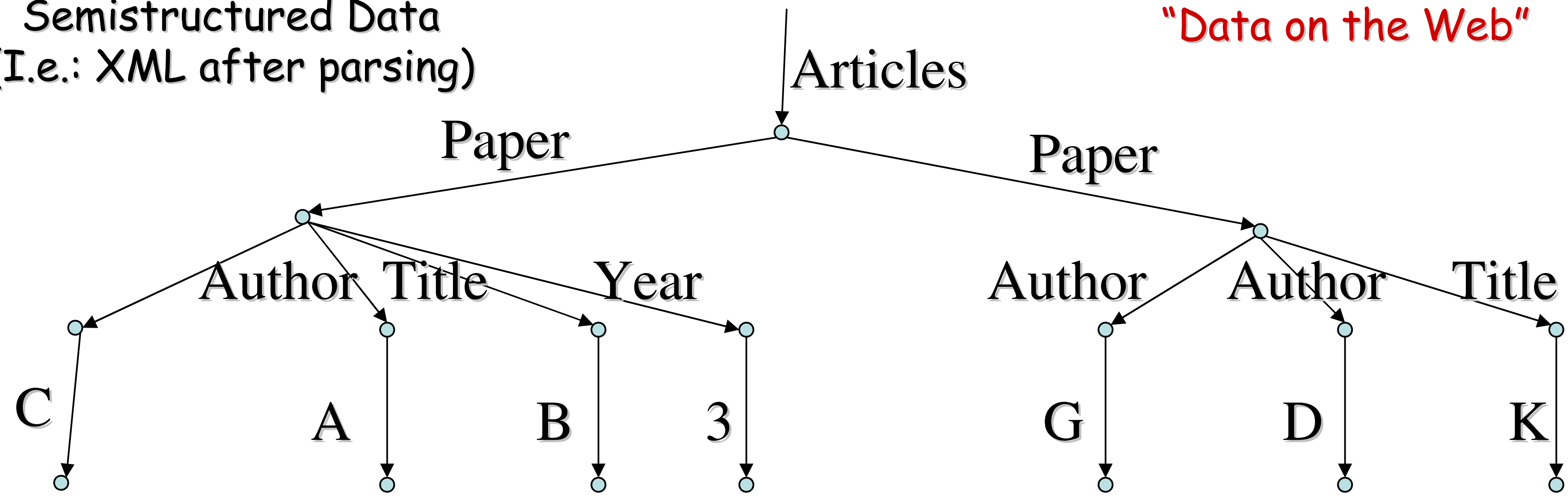
- Protocol contracts
  - Typechecking-style support for checking the interaction of concurrent protocols.
  - A.k.a behavioral type system, session types, etc.
- Required for software reliability
- Facilitated by explicit concurrency interfaces.

Data

DATA

Abiteboul, Buneman, Suciu: "Data on the Web"

Semistructured Data
(I.e.: XML after parsing)



- A tree (or graph), unordered (or ordered). With labels on the edges.
- Invented for "flexible" data representation, for quasi-regular data like address books and bibliographies.
- Adopted by the DB community as a solution to the "database merge" problem: merging databases from uncoordinated (web) sources.
- Adopted by W3C as "web data", then by everybody else.

It's Unusual Data

- Not really arrays/lists:
  - Many children with the same label, instead of indexed children.
  - Mixture of repeated and non repeated labels under a node.
- Not really records:
  - Many children with the same label.
  - Missing/additional fields with no tagging information.
- Not really variants (tagged unions):
  - Labeled but untagged unions.
- Unusual data.
  - Yet, it aims to be the new universal standard for interoperability of programming languages, databases, e-commerce...

Needs Unusual Languages

- New *flexible* types and schemas are required.
  - Based on "regular expressions over trees" reviving techniques from tree-automata theory.
- New processing languages required.
  - Xduce [Pierce, Hosoya], Cduce, …
  - Various web scripting abominations.
- New access methods/query languages required.
  - E.g. Existence of paths through the tree.

Data Descriptions

- We want to *talk about* data
  - I.e., specify/query/constrain/typecheck the possible structure of data, for many possible reasons:
    - Typing (and typechecking): for language and database use.
    - Constraining (and checking): for policy or integrity use.
    - Querying (and searching): for semistructured database use.
    - Specifying (and verifying): for architecture or design documents.
- A *description* (*spatial formula*) is a formal way of talking about the possible structure of data.
  - We go after a general framework: a very expressive language of descriptions.
  - Combining logical and structural connectives.
  - Special classes of descriptions can be used as types, schemas, constraints, queries, and specifications.

Example: Typing

Data

Cambridge[
  Eagle[
    chair[**0**] |
    chair[**0**]
  ]
]

In Cambridge there is (nothing but) a pub called the Eagle that contains (nothing but) two empty chairs.

data matches description

Description

Cambridge[
  Eagle[
    chair[**0**] |
    T
  ] | **T**
]

In Cambridge there is (at least) a pub called the Eagle that contains (at least) one empty chair.

Example: Queries

With match variables $\mathcal{X}$: *Who is really sitting at the Eagle?*

Eagle[
  chair[$\neg\mathbf{0} \wedge \mathcal{X}$] |
  T
]

Yes: $\mathcal{X}$ = *John*[**0**]
Yes: $\mathcal{X}$ = *Mary*[**0**]

With *select-from*:

from Eagle[...]
match Eagle[*chair*[$\neg\mathbf{0} \wedge \mathcal{X}$] | **T**]
select person[$\mathcal{X}$]

Single result:
  person[*John*[**0**]] |
  person[*Mary*[**0**]]

Example: Policies

"Vertical" implications about nesting

"Business Policy"

Borders[
  Starbucks[…] |
  Books[…]
]

Borders[**T**] ⇒
Borders[*Starbucks*[**T**] | **T**]

If it's a Borders,
then it must contain a Starbucks

"Horizontal" implications about proximity

"Social Policy"

Smoker[…] |
NonSmoker[…] |
Smoker[…]

(*NonSmoker*[**T**] | **T**) ⇒
(*Smoker*[**T**] | **T**)

If there is a NonSmoker,
then there must be a Smoker nearby

Example: Schemas

- Descriptions are a "very rich type system". We can comfortably represent various kinds of schemas.
- Ex.: Xduce-like (DTD-like) schemas:

$\mathbf{0}$	the empty tree	
$\mathcal{A} \mid \mathcal{B}$	an $\mathcal{A}$ next to a $\mathcal{B}$	
$\mathcal{A} \vee \mathcal{B}$	either an $\mathcal{A}$ or a $\mathcal{B}$	
$n[\mathcal{A}]$	an edge n leading to an $\mathcal{A}$	
$\mathcal{A}^*$	$\triangleq\ \mu X.\mathbf{0} \vee (\mathcal{A} \mid X)$	the merge of zero or more $\mathcal{A}$s
$\mathcal{A}^+$	$\triangleq\ \mathcal{A} \mid \mathcal{A}^*$	the merge of one or more $\mathcal{A}$s
$\mathcal{A}^?$	$\triangleq\ \mathbf{0} \vee \mathcal{A}$	zero or one $\mathcal{A}$

Ongoing Work

- Freely mixing logic and data: spatial logics

  $a[b[A \vee B]] \Rightarrow a[C]$

  - Can be seen as type systems, query languages, policy specifications, etc.
  - Special cases are regular expressions over trees (XML query, etc.)
  - Lots of open theoretical problems in this area (typing and subtyping algorithms, decidable sublogics, etc.)

~~Xen~~ Cω

```
T ::= N
    |  T[] | T{}
    |  T(…,T,…)
    |  T|T
    |  T*
    |  […, T m,…]
```

arrays

closures

union

streams

tuples (rows)

Protection

Hiding

- Any kind of security/privacy issue has to do with hiding something
  - Hiding procedures by access control
  - Hiding data by encryption
- In programming languages:
  - How can we protect/hide flows? (Security)
  - How can we protect/hide data? (Privacy)
  - Exploit the mother of all hiding operators: π-calculus restriction (already widely used in crypto protocol analysis).

Flow Protection: Group Creation

- *Group creation* is a new general construct that can be added to virtually any language or formalism.
- It is a natural extension of the sort-based type systems developed for the π-calculus:
  - (νG) $(\nu n{:}G)$ $(\nu m{:}G)$ ...
  - create a new group (i.e., unstructured type or collection) G, and populate it with new elements n, m, ...
- A secret like n can never escape from the initial scope of G, as a simple matter of typechecking.

Untrusted Opponents

- Problem: opponents cheat. Suppose the opponent is untyped, or not well-typed (e.g.: running on an untrusted machine):

$(\nu p{:}U) \quad (p(y).O' \quad | \quad (\nu G)\,(\nu x{:}G)\,(p\langle x\rangle \mid P''))$

untrusted name server — untrusted opponent — trusted locally typechecked player

- Will an untyped opponent, by cheating on the type of the public channel *p*, be able to acquire secret information?
- Fortunately, no. The fact that the player is well-typed is sufficient to ensure secrecy, even in presence of untyped opponents. Essentially because $p\langle x\rangle$ must be locally well-typed.
- We do not even need to trust the type of the public channel *p*, obtained from a potentially untrusted name server.

Secrecy Guarantee

- Programmer's reference manual:

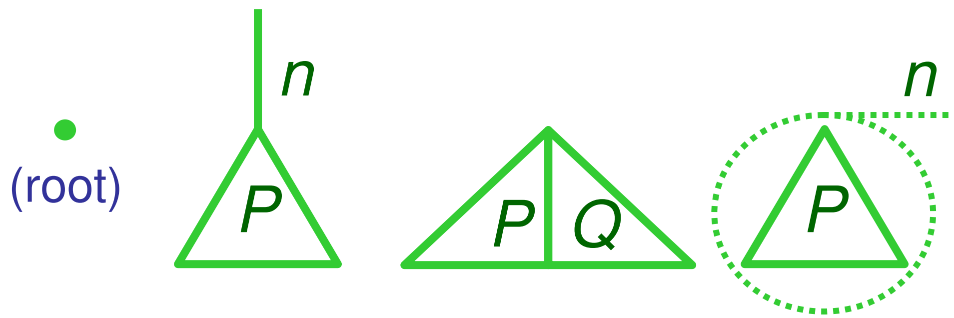
  Names of group *G* remain *secret*, forever, outside the initial scope of (νG).

- Secrecy Theorem (paraphrased)

  If (νG)(νx:...G...)P is well-typed, then P will not leak x even to an untyped (untrusted) opponent.

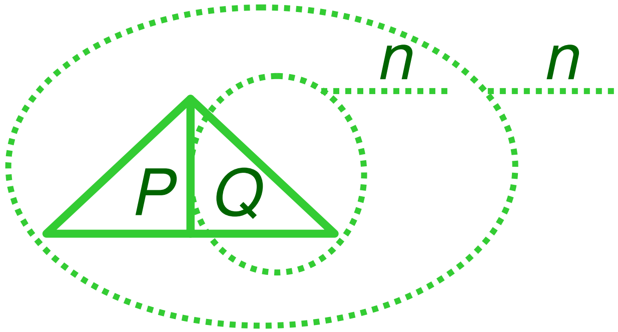
Data Protection: Trees with Hidden Labels

P,Q ::=
- 0
- $n[P]$
- $P \mid Q$
- $(\nu n)P$



Tree Equivalence (Structural Congruence)

- $(\nu n)(P \mid (\nu n)Q) \equiv ((\nu n)P) \mid ((\nu n)Q)$



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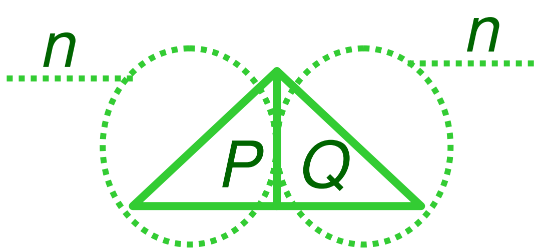
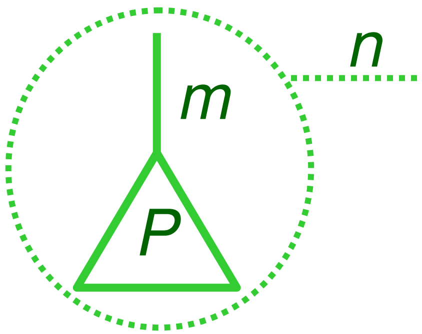


- $(\nu n)m[P] \equiv m[(\nu n)P]$ if $n \neq m$



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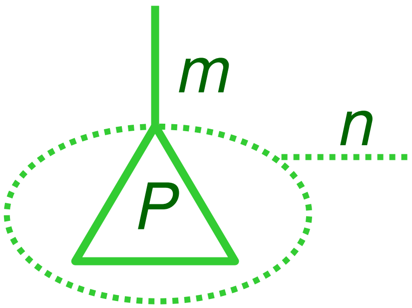
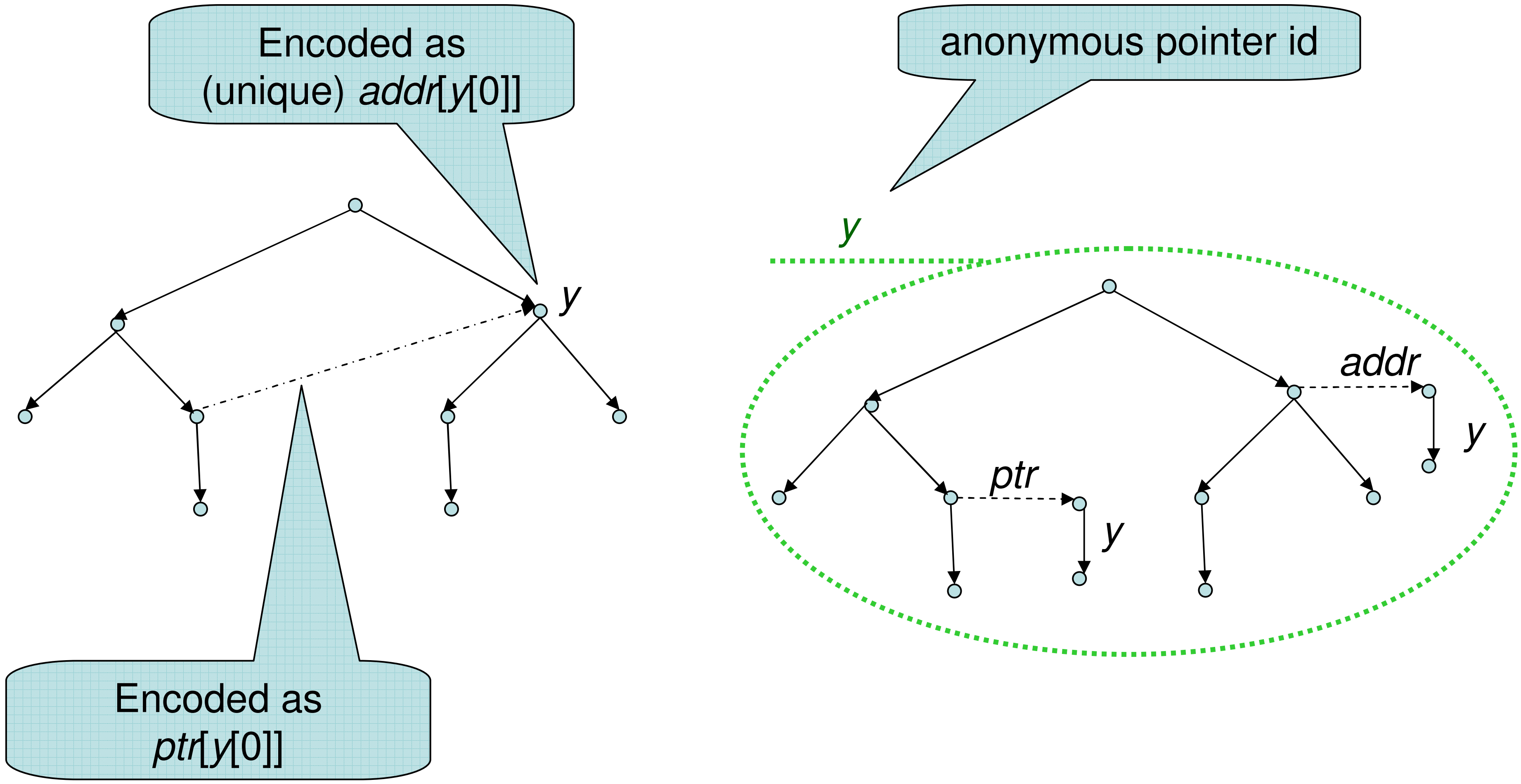
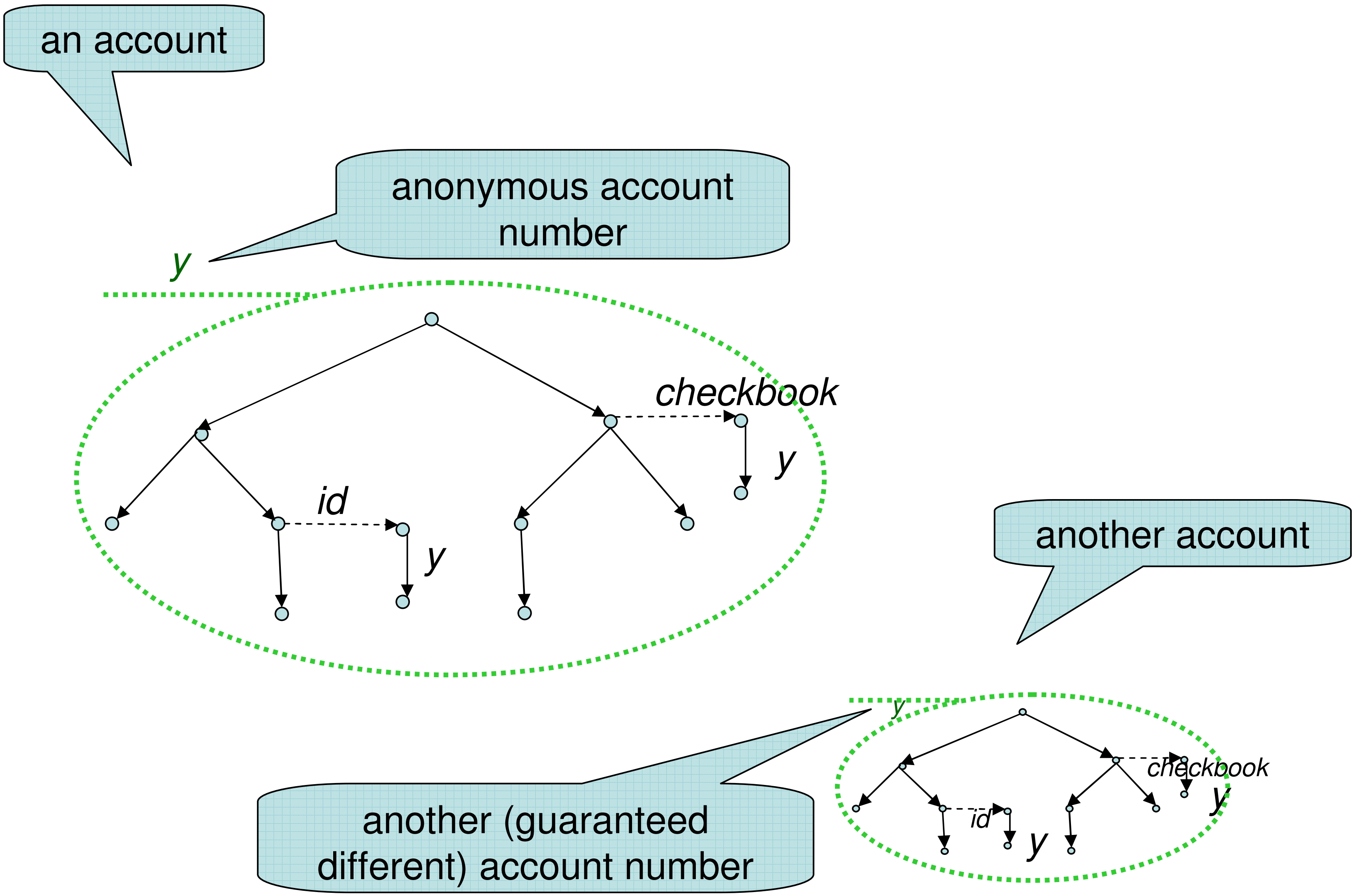


Ex: Local Pointers

- E.g., XML IDREFs



Ex: Unique and Unguessable IDs



Type Systems for Hidden Names

- *account* : H*y*. … *id*[*y*] … *checkbook*[*y*] …

Hiding quantifier

- These are *name-dependent* types
  - Dependent types: traditionally very hard to handle because of computational effects.
  - But dependent only on "pure names": no computational effects.
  - Name-dependent types are emerging as a general techniques for handling freshness, hiding, protocols (e.g. Vault), and perhaps security/privacy aspects in type systems.

Conclusions

WAN Flows, Data, Protection

- New languages
  - Language evolution is driven by wishes.
  - Language adoption is driven by needs.
- We now *badly need* evolution in areas related to WAN-programming for non-experts (i.e. with language support).
  - Concurrent flows.
    - Applications of Join Calculus.
  - Semistructured data.
    - Applications of Spatial Logics.
  - Flow and data protection.
    - Applications of π-calculus restriction.

References

- Flows
  - **Join Calculus**: Fournet *et al.*
  - **Polyphonic C#**: Benton, Cardelli, Fournet.
  - **Behave!**: Larus *et al.* **Vault**: DeLine *et at.*
  - + Kobayashi, Honda, Yoshida, Vasconcelos, …
- Data
  - **Xen/** $C\omega$: Meijer *et al.*, http://www.research.microsoft.com/Comega/
  - **TQL**: Cardelli, Ghelli *et al.*
- Protection
  - **Fresh-ML**: Pitts *et al.*
  - **Secrecy and Groups**: Cardelli, Ghelli, Gordon.
  - **Trees with Hidden Labels**: Cardelli, Gardner, Ghelli.

(See personal web pages or search engines.)